DOI: 10.46551/rc24482692202504

Revista Cerrados ISSN: 2448-2692

https://www.periodicos.unimontes.br/index.php/cerrados

Landscape modeling through remote sensing data for central and western Bahia, Brazil

Modelagem de paisagens através de dados de sensoriamento remoto para o centro e oeste baiano, Brasil

Modelado del paisaje mediante datos de teledetección para el centro y oeste de Bahía, Brasil

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Abstract

This study presents a discussion on the spatial modeling of landscapes through remote sensing techniques, initially presenting a conceptual discussion on the topics related of modeling, remote sensing, and landscapes. The study offers the following research question: How to represent the diversity of landscapes with their environmental components that are sensitive to anthropic actions in central and western Bahia? Given this issue, the research the general purpose of: representing the points with the highest environmental vulnerability. The study area of this research corresponds to the areas located in the central portion, alongside the western territory of the state of Bahia, Brazil. Through procedures encompassing remote sensing and digital image processing, it was possible to achieve the result to generate and quantify a representative model for the aspects of land cover which enabled analysis and subsequent recommendations for environmental issues inherent to the reality of the investigated area.

Keywords: Vegetation index. Morphology. Geotechnologies and Environments.

Resumo

Este estudo apresenta uma discussão sobre a modelagem espacial de paisagens mediante o uso de técnicas de sensoriamento remoto, abordando, inicialmente, uma discussão conceitual sobre os temas de modelagem, sensoriamento remoto e paisagens. O estudo apresenta como questão de pesquisa: como representar a diversidade de paisagens com seus componentes ambientais sensíveis a ações antrópicas no Centro e também no Oeste baiano? Diante dessa questão, a pesquisa possui como objetivo geral: representar os pontos com maior vulnerabilidade ambiental na área de estudo. A área de estudo desta pesquisa corresponde à porção central agregada ao Oeste do território do estado da Bahia. Por meio de procedimentos como sensoriamento remoto e processamento digital de imagens, foi possível alcançar, como resultados, a geração e a quantificação de um modelo representativo dos aspectos de cobertura da terra. Esse modelo possibilitou análises e posteriores recomendações para questões ambientais inerentes à realidade da área investigada.

Palavras-chave: Índices de vegetação. Morfologia. Geotecnologias e Ambientes.

Resumen

Este estudio presenta una discusión sobre el modelado espacial de paisajes mediante el uso de técnicas de teledetección, abordando inicialmente una discusión conceptual sobre los temas de modelado, teledetección y paisajes. El estudio presenta como pregunta de investigación: ¿cómo representar la diversidad de paisajes con sus componentes ambientales sensibles a las acciones humanas en el Centro y también en el Oeste de Bahía? Frente a esta problemática, el objetivo general de la investigación es representar los puntos de mayor vulnerabilidad ambiental en el área de estudio. El área de estudio de esta investigación corresponde a la porción central agregada al Oeste del territorio del estado de Bahía. A través de procedimientos como la teledetección y el procesamiento digital de imágenes, se logró lograr, como resultados, la generación y cuantificación de un modelo representativo de aspectos de cobertura del suelo. Este modelo permitió realizar análisis y posteriores recomendaciones sobre cuestiones ambientales inherentes a la realidad de la zona investigada.

Palabras-clave: Índices de vegetación. Morfología. Geotecnologías y Ambientes.

Introduction

We live in an era marked by a wide variety of technologies, in particular those aimed at investigating environmental issues, such as geotechnologies. In this scenario, Ângelo (2015) argues that the current challenge of spatial data representation consists of the computational search for the dynamics of territorial processes. Thus, these actions extend beyond the simple insertion of a time series into computational databases – the challenge consists of transforming these systems, which are essentially static, into tools that are capable of providing realistic representations of “spatiotemporal” processes (Burrough, 1998). With that, this occurs through the understanding of factors and laws that govern the dynamics to be observed in the landscape, particularly when this is the main topic of the research that employs such geotechnologies (Lana, 2009; Pedrosa, 2004; Ângelo, 2015).

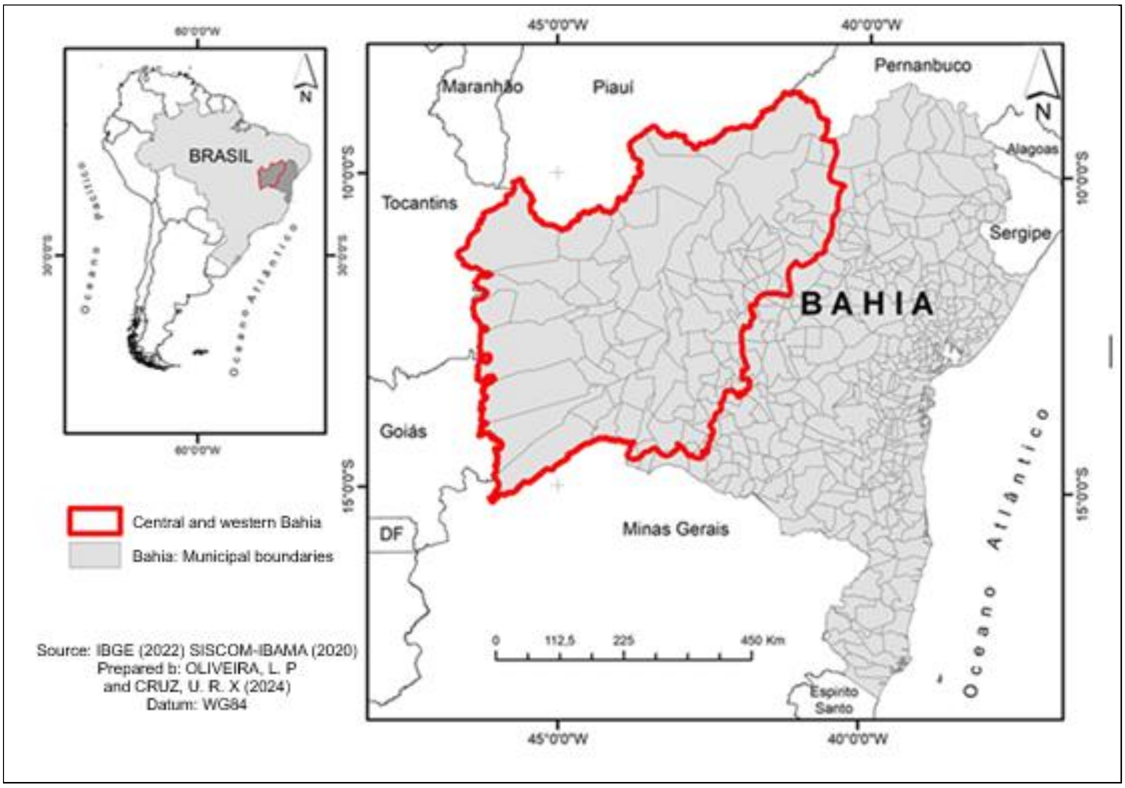
In the context of geotechnologies and modeling, for the purposes of this study, we employed remote sensing, which can be broadly defined as one of the ways to acquire information regarding an object or target on Earth's surface, without establishing any physical contact with it (Barros et. al.; 2016). Remote sensors make it possible to collect energy originating from the object on the surface, convert it into a signal that can be recorded, and present it in a suitable way for extracting information. This technology has been used in various areas of knowledge, thanks to the possibility of obtaining a large amount of information about an area or an ecosystem at different times, at a low cost, compared to other forms of study that require more fieldwork and good quality, allowing for the integrated visualization of the environment, among other benefits (Novo, 1992; Florenzano, 2002).

Here, the landscape is understood as the set of natural elements, expressed through a spatial arrangement representing the current stage of a dynamic over a given long period of time (Troll, 1982). In this way, the landscape can be understood in a classical way, according to Troll (1982), i.e., as a form, functionality, and transformation (Oliveira and Suertegaray, 2014, p.213). In this sense, the topic of the landscape finds in computing-based remote sensing and spatial modeling a methodological framework in a constant evolutionary process, based on the improvement of techniques, methods, and resources that are increasingly capable of providing answers to questions related to environmental, territorial and many other issues in which the use of geotechnologies and computing is applied (Novo, 1992; Veldkamp & Fresco, 1996; Verburgh et al., 2002; Florenzando, 2002; Soares-Filho et al, 2006).

This study raises the following research question: How to represent the diversity of landscapes with their environmental components that are sensitive to human actions in central and western Bahia? In view of this issue, the research has the general purpose of representing the points with the greatest environmental vulnerability in the study area. To this end, the following specific purposes were defined: i) To develop a database for the study area; ii) to investigate aspects of vegetation cover and land use through vegetation and composition indices; and iii) to identify areas that are ecologically sensitive to human activities. The study area of this research comprises the areas located in the central area, alongside the western territory of the state of Bahia, limited to the Brazilian states of Piauí, Tocantins, Goiás, and Minas Gerais (to the south), as illustrated in

Map 1.

Map 1: Location of the study area



Source: Authors' own work, 2025.

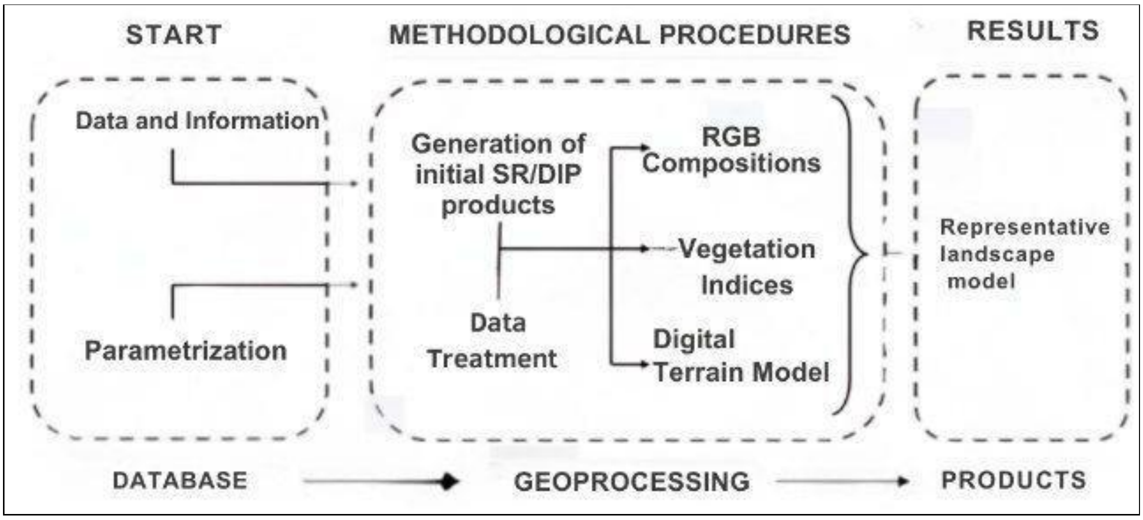
This region is strongly influenced by the Caatinga and Cerrado biomes, which are marked by the presence of the São Francisco River. The area is characterized by the predominance of agribusiness, with agriculture and livestock activities at various levels of production. Given this environmental scenario, it is appropriate to apply spatial modeling and remote sensing for the purpose of investigating the complexity of the landscape.

The choice of this area for the intended study was motivated by the potential for applying modeling and remote sensing in this part of the state of Bahia. The climatic characteristics and atmospheric conditions allow the use of these techniques during most of the year, as the region has a reduced influence of atmospheric phenomena, such as clouds, which hinder the application of sensing for capturing images. It is crucial to highlight that studies involving the use of remote sensing find local atmospheric conditions a determining factor for their execution and the subsequent production of results.

Methodology

The methodological procedures of this research are based on the modeling concepts of Burrough (1998) and Soares-Filho et al. (2006). Thus, modeling is used as a tool for processing data and information in order to fulfill the purposes of this study. In summary, the work of this research was systematized in three stages: 1) definition of data and information, followed by parameterization and definition/construction of the database; 2) processing or geoprocessing of the data used, performed in a Desktop x64 computing environment using the free x64 software program (QGIS 3.22); and 3) generation of products for discussion of the results (representative models), as illustrated in Figure 1.

Figure 1: Flowchart of the research's methodological procedures



Source: Authors' own work, 2025.

The study area was defined based on the feasibility of using the scene (image) obtained by the AMAZÔNIA 1 satellite, equipped with a wide field of view imaging camera (sensor) (Wide Field Imager – WFI). Images captured with low interference from atmospheric phenomena (clouds and air humidity) and those that framed the intended area, corresponding to the scene within orbit point 034/017 as of July 18, 2023, were considered. The preliminary data used in this study are composed of vectors and polygons related to the study area, such as municipal and state boundaries, watercourses, roads, highways, and sites, distributed online by institutions such as the Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e*

Estatística – IBGE), the Brazilian Institute of Environment and Renewable Natural Resources (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis* – IBAMA), and the Superintendent's Office of Economic and Social Studies of the State of Bahia (*Superintendência de Estudos Econômicos e Sociais da Bahia* – SEI-BA (Table 1).

Table 1: Summary of sources/suppliers used in the research

Distributor / ACRONYM		**URL FOR ONLINE ACCESS**
Brazilian Institute of Geography and Statistics	IBGE	https://www.ibge.gov.br/geociencias/downloads-geociencias.html
National Institute of the Environment	IBAMA	https://dadosabertos.ibama.gov.br/dataset/?page=1
Mapbiomas.org	Mapbiomas	https://brasil.mapbiomas.org/downloads/
Superintendent's Office of Economic Studies of Bahia	SEI-BA	https://portal.geo.sei.ba.gov.br/portal/apps/sites/#/seigeo

Source: Authors' own work, 2025.

The raster data were acquired through the portal of the Image Generation Division of the National Institute for Space Research (*Divisão de Geração de Imagens do Instituto Nacional de Pesquisas Espaciais* – DGI/INPE), available for download on the Internet [www.dgi.inpe.br] (INPE, 2021). The scene used to cut out the study area was acquired at the L-4 processing level, previously orthorectified, i.e., an image with radiometric correction and geometric system correction, refined by the use of control points and a digital terrain elevation model (Marcari-Junior, 2013; Silva, Grande, Oliveira, 2022; Feitosa et. al,, 2023 and INPE, 2021). The four acquired bands correspond to the characteristics described in Table 2.

Table 2: Characteristics of the image from the AMAZÔNIA-1 satellite with the WFI sensor used in the research

Band No.	Spectral Range	Quantization	Spatial Resolution	Image Range	Reference System	Revisit
BAND 1	*Blue (0.45 – 0.52 µm)*	16 bits	64 m	850 km	Datum WGS 1984	5 days
BAND 2	*Green (0.52 – 0.59 µm)*					
BAND 3	*Red (0.63 – 0.69 µm)*					
BAND 4	*NIR (0.77 – 0.89 µm)*					

Source: Authors' own work, 2025.

After image acquisition, they were submitted to the digital image processing (DIP) stage for treatment and generation of products from the manipulation of the bands. The QGIS 3.22 x64 software was used to process the raster images.

Atmospheric correction procedures were performed (GAIDA, 2020), aiming to correct and attenuate the influence of atmospheric effects on the images. For this purpose, the correction by the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) method (Chandrasekhar, 1960; Tanré et al., 1990; Vermote et al., 2006; and Gaiada, et. al., 2020) was used, being implemented in the Geographic Resources Analysis Support System (GRASS) (GRASS Development Team, 2018), through the i.atcorr extension (Zietsman et al., 2018; Gaiada, et. al., 2020). After the atmospheric correction stage, the remote sensing data and information produced by the DIP enabled the generation of the following products: Vegetation Indices (VIs) (Novo, 1992; Jansen, 2002; Florenzano, 2002; Ponzoni, Shimabukuro, Kuplich, 2015), Digital Terrain Models (DTM) (Zhilin, 2004; Farr et. al., 2007; Macedo, Surya, 2018), and Representative Landscape Models (Cavalcanti, 2014; Camara et. al., 2015).

Based on the references mentioned above, this study employed two vegetation indices during the tests: 1) Normalized Difference Vegetation Index (NDVI); and 2) Soil Adjusted Vegetation Index (SAVI). Both were calculated in the raster calculator environment of the QGIS 3.22 x64 software program (Table 3).

Table 3: Mathematical formulas for calculating the Vegetation Indices used in the study.

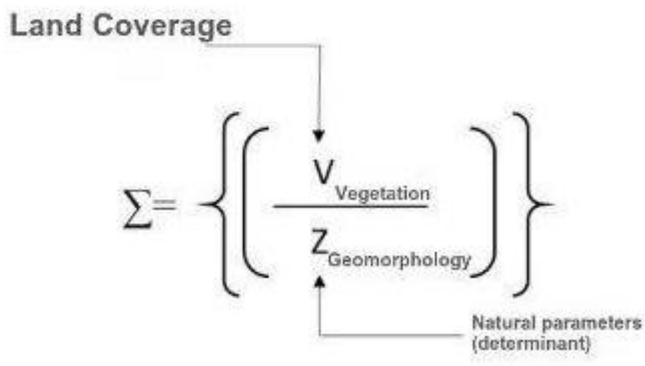
A)	B)
$NDVI = \sum = \left(\frac{\rho NIR - \rho Red}{\rho NIR + \rho Red} \right)$	$SAVI = \sum = \left(\frac{\rho NIR - \rho Red}{\rho NIR + \rho Red} \right) x \left(1 + \rho L \right)$

Source: Authors’ own work, 2025.

After calculating the vegetation indices and organizing these products in the project’s geographic database in the software environment, the images produced (VIs and RGBs) were superimposed in a three-dimensional (3D) visualization environment, using as a basis the model derived from the Shuttle Radar Topography Mission (SRTM) with an original resolution of 90 m, resampled to 30 m, using the World Geodetic Survey 1984 – WGS84 reference system (DUREN et. al., 1998).

The basic principle for preparing the Simplified Landscape Representation Model (SLRM) consists of using VIs and DTMs superimposed on a database structure for three-dimensional (3D) visualization, including the morphological layer is the DTM and the other layers are secondary overlays. To generate the SLRM, it is necessary to equate the data used (VIs and DTM) through equivalence and standardization of projection, datum, format, and measurement unit of the layers (Figure 22).

Figure 2: Equation of the Simplified Landscape Representation Model (SLRM)



Source: Authors' own work, 2025.

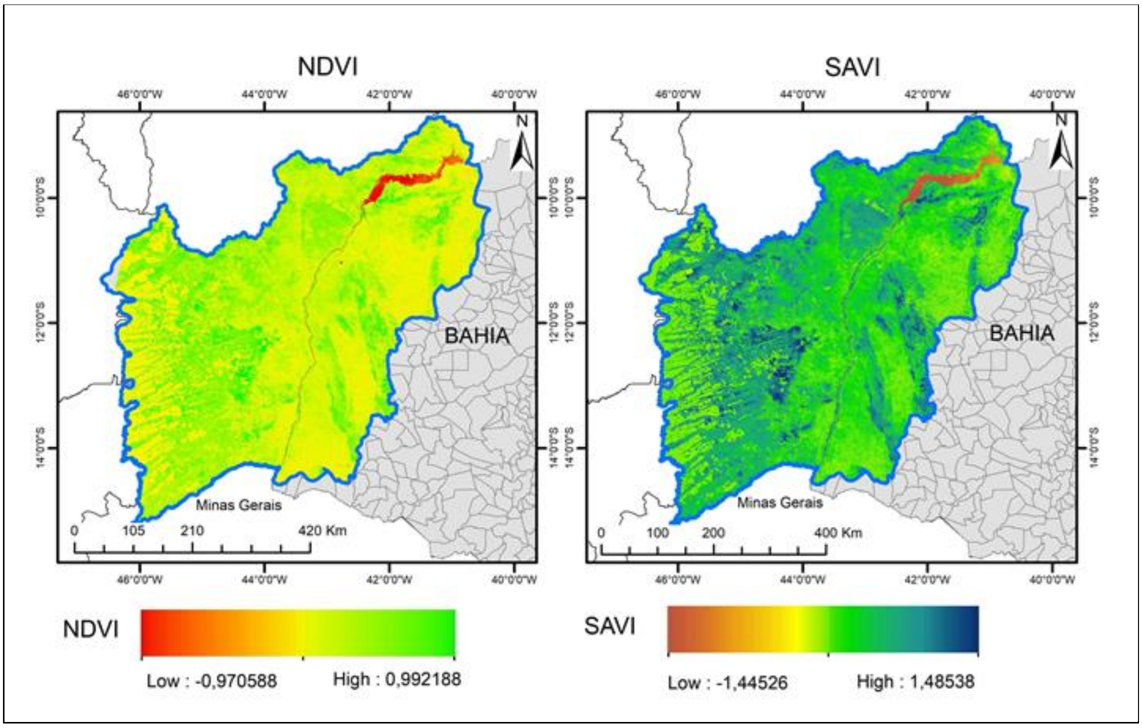
Based on the 3D model developed, with the added layers and classes (VIs, DTM, and polygons), it is possible to interpret the results of the study. It is important to consider that the numerical data/products (tabular values) were submitted to the OpenOffice Calc spreadsheet software to perform mathematical operations and generate graphs. These were used during the landscape reading, since they integrate the products of the spatial modeling performed.

Results and discussions

This study presented environmental information and spatial modeling products as results with the purpose of representing points of environmental vulnerability throughout the study area, in addition to a simplified landscape model (SLM) that makes it possible to represent the existing complexity. Regarding the initial products (data and information), the Vegetation Indices (VI) stand out, being generated from data from the WFI sensor of the AMAZONIA 1 satellite, associated with the Digital Terrain Model (DTM) of the study area. These data were integrated to result in the final product, i.e., the SLM.

The first product generated (calculated) was the Normalized Difference Vegetation Index (NDVI). This consists of an index based on the normalized difference in vegetation. The NDVI made it possible to identify areas with varying levels of vegetation, considering physiognomic and taxonomic characteristics of the local flora. This index indicated areas with smaller vegetation and density, as well as differentiated photosynthetic activity, indicating points of fragility/vulnerability. The NDVI values ranged from a maximum of 0.99 µm, for greener and more vigorous vegetation, to a minimum of -0.97 µm, for low-lying, more stressed vegetation, reaching the absence of vegetation or exposed soil (Map 2).

Map 2: Comparison between Vegetation Indices

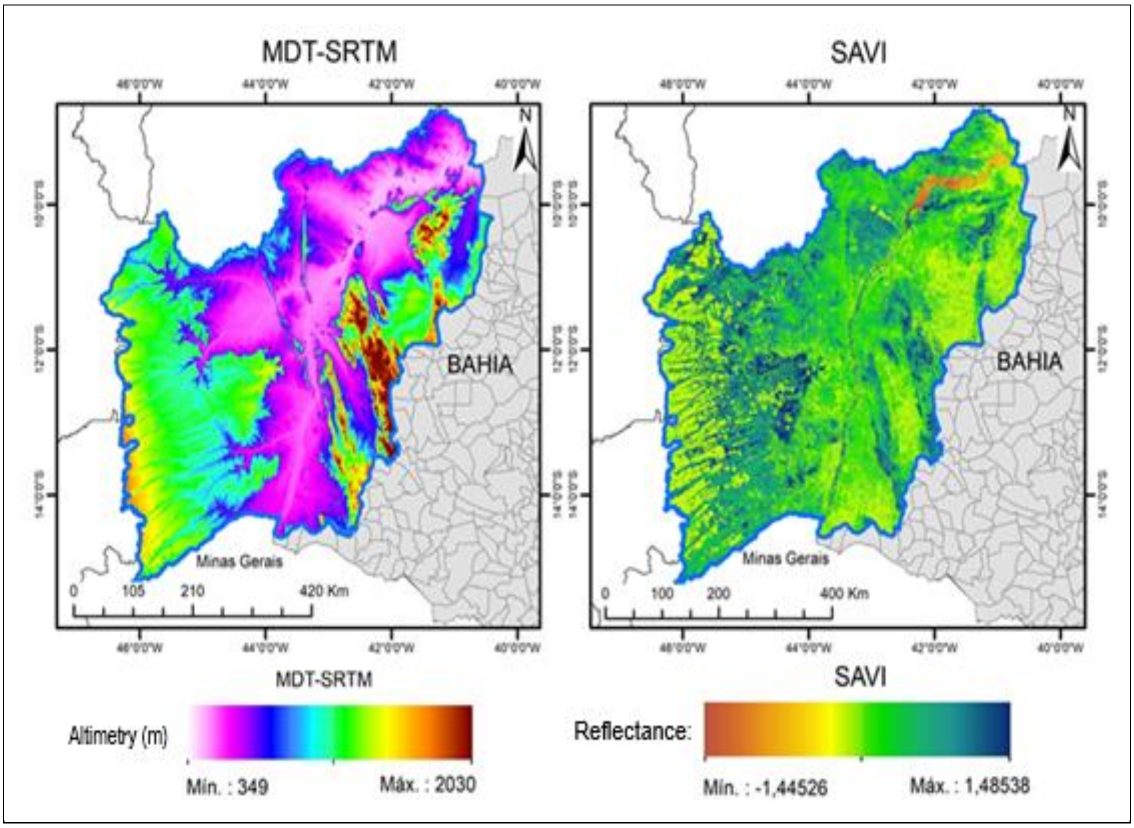


Source: Authors’ own work, 2025.

As is the case with the NDVI, the Soil Adjusted Vegetation Index (SAVI) was also used, consisting an index adjusted for the soil, indicated for semiarid areas or areas with less dense vegetation and a greater tendency to water stress and, mainly, for areas with less dense vegetation cover and drier areas. It is also present in areas with more exposed soil, in contrast to humid areas. The SAVI presented minimum values of -0.90 µm for points with vegetation characterized by Cerrado, Caatinga, and Extensive Pastures, with maximum values of 1.44 µm for areas with fragments of native vegetation and points of intensive agriculture with crops under development.

Seeking an overall analysis of the landscape of the study area, both indices, NDVI (ranging from 0.99 µm to -0.97 µm) and SAVI (from 1.44 µm to -0.90 µm), were superimposed on a Digital Terrain Model (DTM) with elevations between 349 m and 2,030 m above sea level. The relationship between VIs and DTM allows the analysis of the relationships between vegetation cover and the morphology of the area. In this study, it was possible to identify associations between terrain irregularity and higher VI values (Map 3).

Map 3: Relief and vegetation cover in the study area.

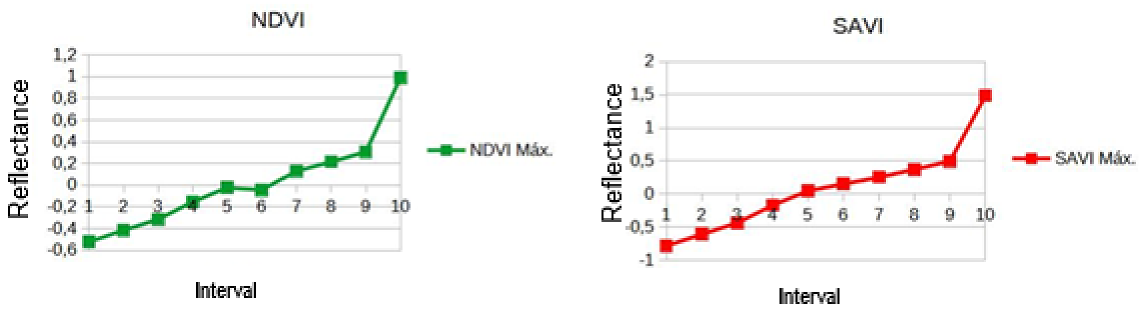


Source: Authors' own work, 2025.

The areas affected by anthropogenic activity, mainly those with activities such as agriculture and extensive pastures, are located in the far west of the study area. In these areas, despite the incidence of relative plateaus, the average altitudes are approximately 700 m. These areas presented SAVI values between -0.99 µm and 1.3 µm (maximum and minimum), indicating vegetation cover of an anthropogenic nature, such as grain and cotton crops, which predominate in the region. The study area is undergoing an intense process of landscape transformation, mainly due to the expansion of agriculture, which has resulted in marks left on the landscape through the exposure of the soil and the reduction of native vegetation (Cerrado to the west and Caatinga to the east). The calculation of the SAVI and NDVI indices allowed the graphical representation of their behaviors and values, as illustrated in Chart 1.

Chart 1: NDVI and SAVI indices calculated for the study area

A) B)

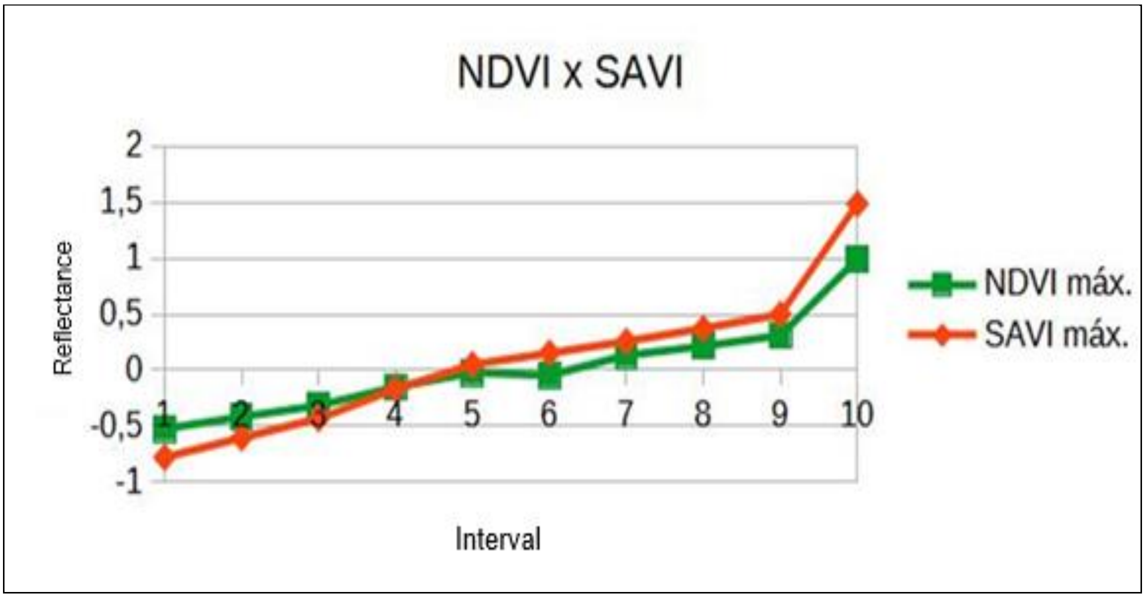


Source: Authors' own work, 2025.

The NDVI index (Chart 1-A) presented a minimum of -0.6 µm for areas with a total absence of vegetation cover, such as exposed soils and water bodies, and a maximum of 1 µm for specific points in the landscape with dense vegetation and/or tree size, located mainly in more remote areas, due to the influence of the relief with higher altitudes (< 900 m). The SAVI index, represented by Chart 1-B, allows validating/confirming the NDVI readings and interpretations. The SAVI presented a minimum value of -1 µm and a maximum value of 1.5 µm, the minimum corresponding to non-vegetated areas, while the maximum corresponds to vegetated areas with high photosynthetic activity, meeting the same altimetric standards analyzed, when paired.

For this study, the systematic analyses of the elements and factors that comprise the landscape are highlighted, using the theory of geosystems (Bertalanfy, 1975, and Bertrand, 1978) as a reference. Thus, the SAVI and NDVI analyses were carried out in parallel. In this way, it was possible to verify approximations of the reflectance values (μm) in relation to the intervals in the graph of the study area. When comparing the VIs, a greater regularity of the SAVI values is observed. The NDVI showed a variation between the most central intervals in Chart 2:

Chart 2: Representation of the set of NDVI and SAVI vegetation indices in the study area

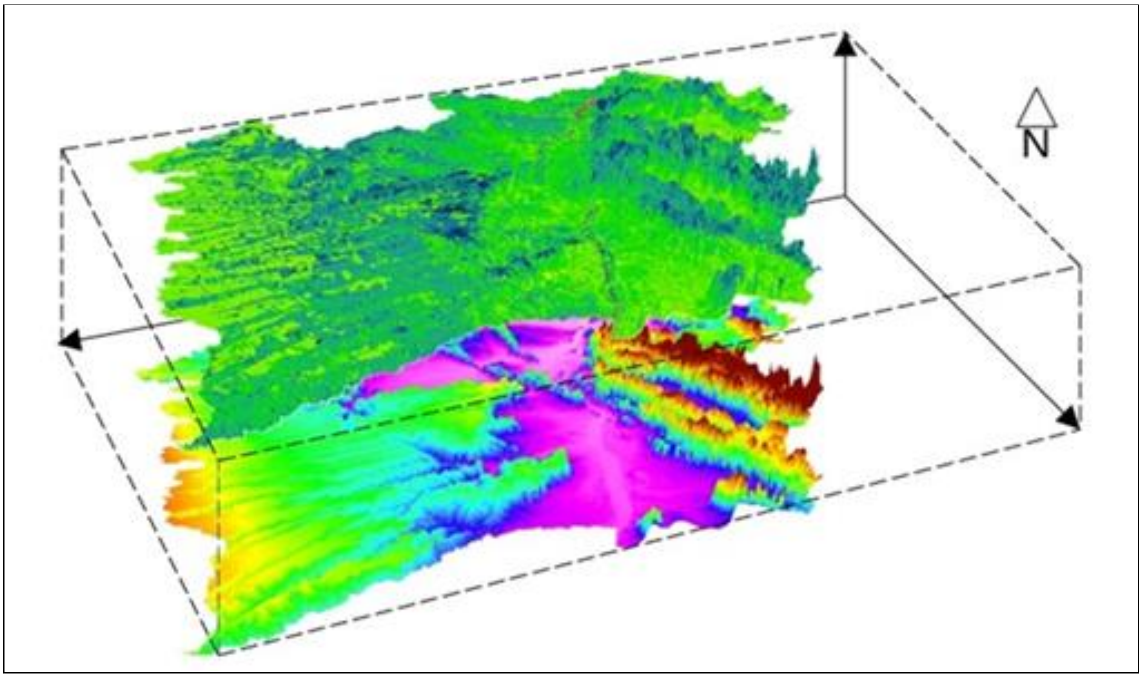


Source: Authors' own work, 2025.

The values represented previously in Graph 2 illustrate the complexity of the vegetation cover in the study area, as the vegetation presents variations that indicate points of vulnerability, mainly in the areas with lower values (> -0.5 μm) and fragments with higher values (< 0.5 μm), isolated due to the relief with elevations below 800 m. From this information, it was possible to generate a three-dimensional (3D) representation of the study area, in order to enable an integrated analysis of the landscape, considering the overlapping relief and land cover elements (

Map 4).

Map 4: Three-dimensional perspective of the landscape of the study area



Source: Authors' own work, 2025.

The 3D representation of the landscape made it possible to identify the relationship between vegetation cover and relief, highlighting points of environmental vulnerability. These points are characterized by the loss of native vegetation cover and proximity to points of intensified anthropism, such as crop fields and areas of exposed soil. The 3D modeling made it possible to identify remnants of native vegetation, mainly to the east of the study area, where the topography, altitudes, and climate make intensive agriculture unfeasible, as occurs in the western end. Thus, it can be inferred that the morphology of the terrain exerts an influence on the presence and maintenance of environmental preservation in the investigated area. The São Francisco River impacts the landscape of the region, as well as the fractions of Serra do Espinhaço and Serra do Sincorá, to the east.

The use of 3D modeling through DTM and VI – comprising mainly SAVI, thanks to the adjustment of local environmental conditions – has become a viable tool for integrated analysis of the landscape, considering both the existing natural systems and human labor through agricultural and pastoral activities. Thus, based on the 3D modeling performed, the consolidation of the Simplified Landscape Model (SLM) for the study area is considered, indicating points of fragility in the far west, in areas intended for agriculture, and in the east, in the fraction of the area with rugged relief and higher elevations, where it was possible to detect more preserved and dense fragments of native vegetation.

During the analysis of the VIs on the surface of the municipalities, it was possible to observe that the municipalities located in areas of relevance for agribusiness through the cultivation of soybeans, corn, and cotton (Luís Eduardo Magalhães, Barreiras, Formosa do Rio Preto, Roda Velha, and São Desiderio) located in the far west region of the state of Bahia presented NDVI with reflectance values, comprising a minimum of -0.970 µm and a maximum of 0.992 µm and the SAVI with a minimum of -1.445 µm and a maximum of 1.485 µm. These reflectance values (µm) are the result of vast areas of cultivation, demonstrating intensified use of the soil by agricultural activities. Such indices (NVDI and SAVI) indicated approximate values (-0.970 µm ~ 0.992 µm and -1.445 µm ~ 1.485 µm) in the areas of the municipalities of Gentio do Ouro, Souto Soares, Iraquara, and Mulungu do Morro, where the vegetation cover showed levels of potential and relevant vigor, thanks to the climatic conditions, with the presence of humidity and rainfall, which are inherent in high altitudes (< 850m ~ 2080m). It was possible to note that in the extreme longitude directions of the study area, the vegetation is influenced by climate, as well as by altitudes (< 750m / 0.800 µm). As shown in Table 4 below.

Table 4: Quantification of vegetation index values, relief, and municipalities.

Coverage area fraction	Number of municipalities	DTM-SRTM (m)		NDVI (µm)		SAVI (µm)	
		Max.	Min.	Max.	Min.	Max.	Min.
10.5%	9	1,014	2,030	0.992	-0.970	0.770	-1.440
19.5%	16	647	746	0.780	0.520	0.160	-0.480
35%	29	349	451	0.650	-0.970	1.200	-1.440
40%	33	757	1013	0.720	-0.430	1.043	-0.980

Source: Authors' own work, 2025

The municipalities in the central portion of the study area, which are belonging to the São Francisco River Valley – mainly Barra, Bom Jesus da Lapa, Paratinga, Ibotirama, Moquém do São Francisco, Xique-Xique, Sobradinho, Pilão Arcado, and Remanso, among others – have a vegetation cover with stable reflectance values comprising -0.802 µm ~ 0.992 µm for NDVI and -1.020 ~ 1.030 µm for SAVI. The values mentioned for the indices indicate an area with vegetation cover that differs from the municipalities located at the eastern and western ends of the study area. The relationship between vegetation indexes (NDVI and SAVI) and the morphology of the region (DTM) made it possible to identify the variation in vegetation cover in the area, as well as aspects of the relationship between municipal limits, environments (altitudes and vegetation cover), and characterization in the landscape. The investigation of the relationships between vegetation indices and the digital terrain model used (NDVI, SAVI, and SRTM) demonstrated the importance and influence of altitudes in the formation of vegetation cover and its impact on its uses (agriculture and extensive livestock farming). It was possible to identify fractions of municipalities and their relationship with altitudes (relief) and vegetation indices (Table 3).

Final remarks

This research made it possible to improve the use of geotechnologies applied in the authors' routine. In addition to promoting the exercise of geographic and geotechnological knowledge, this study allowed the experimentation of special modeling techniques, which had already been discussed by the authors at previous times and in previous publications.

It is crucial to highlight the recommendation to continue environmental monitoring work in the study area, using simplified spatial modeling (SLM) resources and other techniques that are able to produce useful information. This information can assist both the State (specific agencies) and civil society (NGOs, among other agents) in the search for improvement in the monitoring, preservation, and management of western and central Bahia.

Acknowledgements

The article was written with the support of the Coordinator's Office for the Improvement of Higher Education Personnel – Brazil (*Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* – CAPES) – Financing Code 001" – Postdoctoral Institutional Program (*Programa Institucional de Pós-Doutorado* – PIPD).

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Article received: January 4, 2025.

Article accepted: March 28, 2025.

Article published: April 1, 2025.